BioScience

Integrating Theoretical Components: A Graphical Model for Graduate Students and Researchers

Journal:	*BioScience*
Manuscript ID:	11-0017.R2
Manuscript Type:	Thinking of Biology
Date Submitted by the Author:	n/a
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Key words:	domain, integration, philosophy of science, theory, ecology
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Coauthor contributions: All coauthors wrote sections and edited drafts of this manuscript. David Choate and Chelse Prather took the lead on a significant portion of the writing and editing for this paper. Matt Michel worked on the section describing the model, tables and figures. Ashley Baldridge and Matthew Barnes drafted the introduction. David Hoekman wrote the section on the model example. Christopher Patrick and Janine Rüegg drafted the discussion. Todd Crowl gave overall guidance on this project and edited several drafts. This manuscript is the product of a graduate seminar on Philosophy of Ecology at the University of Notre Dame.

Abstract

Recent work identifies principles representing the broadest conceptual domains within ecology, which encompasses extremely broad spatial and temporal scales. These broad scales present challenges to maintaining conceptual and theoretical clarity yet theory development requires clear understanding of theoretical components. Although researchers often test hypotheses using existing theories, many endeavors could benefit from a formal structure for examining the theoretical underpinnings of their research. We present a graphical model to organize the theoretical components underlying any particular research effort. We provide an example and suggest that scientists use this framework to present their research in a robust theoretical context. The benefits of this approach include: accurately defining theoretical components used in research; identifying novel questions while avoiding redundancy; and explicitly linking constituent theories, thereby facilitating integration. Many scientists aspire to impact existing theory, and using this approach provides a succinct framework to identify how an individual's research affects ecological theory.

Keywords: domain, ecology, integration, philosophy of science, theory

Introduction

Recently, scientists have suggested sets of fundamental principles representing the widest domains of biology in general (Scheiner 2010), and ecology specifically (Dodds 2009, Pickett et al 2007, Scheiner and Willig 2011). These domains, especially those encompassed by ecology, span numerous levels of biological organization (e.g., microbes to mammoths) over extremely broad spatial (individuals to ecosystems) and temporal (minutes to millenia) scales. As a result of the wide spatial and temporal time scales that ecology attempts to explain, conceptual confusion and the lack of clear, formalized theories represent a challenge to ecological science (Shrader-Frachette and McCoy 1993, Pickett et al 2007, Reiners and Lockwood 2010). Context-dependent results suggest to some that there are no general rules in ecology (Peters 1991, Shrader-Frachette and McCoy 1993), but a fundamental need exists for ecologists to better understand the broadest conceptual and theoretical frameworks that underpin their research to address some of the conceptual challenges these broad domains present.

Belovsky et al. (2004) identified several conceptual issues and provided ten suggestions to improve the advancement of ecological science. Several common themes emerged from their assumptions including the need for: clearer definitions of concepts (but see Hodges 2008), better links between theoretical and empirical research, and more comparative studies over space and time. While Belovsky et al. (2004) provided a compelling list of suggestions and other scientists and philosophers have been critical of progress in ecology (Peters 1991, Allen and Hoekstra 1992, Schrader-Frachette and McCoy 1993, Cuddington and Beisner 2005), they provided no formal framework for individuals to facilitate ecological progress.

Many ecologists informally delineate the theory underlying their research hypotheses while designing their research. This delineation of theoretical components is important to both experiments that directly manipulate factors to test hypotheses, and observational work that examines patterns of response variables over various levels of important factors (e.g. gradients of latitude, moisture, biotic variation, etc). Increasingly, scientists seek to determine the relative importance of different processes on already established patterns, for example, the relative role of predators and nutrients on a prey species' population dynamics (see example below). In cases like these, where multiple factors are known to be important to a process, there might not be a specific a priori prediction (e.g., predation is 10x more important than nutrients), but rather a desire to test general hypotheses concerning the relative importance of multiple drivers (e.g., under what conditions are different drivers dominant). Graduate course work and committee members often lead students through the process of developing studies to effectively test hypotheses.

In a text widely used for experimental design courses, Ford (2000) extensively describes how students should use a scientific method for developing ecological hypotheses, and the role of existing theory in experimental design. However, the experimental design approach to ecology often emphasizes logistical realities over the theoretical foundation of research hypotheses. Consequently, many papers, presentations, and proposals seem to lack a solid understanding of basic ecological theories, a trend noticed by us as well as other authors (Cuddington and Beisner 2005). Cuddington and Beisner (2005) further attribute this phenomenon to the technological movement towards electronic papers leading to a loss of older literature, especially with younger researchers. Failure to understand prior work can lead to wasted research effort and resources, resulting from "reinvention of the wheel" and failure to make appropriate linkages to relevant sub-disciplines of ecology.

In their book, Ecological Understanding: the Nature of Theory and the Theory of Nature, Pickett et al. (2007) emphasized the need for the development of formal theory to encourage integration within and among disciplines. During discussions of this book in a graduate seminar, we found the crucial first step of defining the theoretical components and boundaries of our own research to be quite challenging (see also Prather et al. 2009, Crowl 2009). Like many other students and faculty struggling through this process, we had many "eureka" moments of realization when we understood how our individual research fit into theory developed by other sub-disciplines of ecology or even entirely different disciplines. In this paper, we describe a graphical model that can be used to help identify and organize the various facets of theory underlying research endeavors. Explicitly mapping out these ideas greatly facilitates attaining these "eureka" moments. Therefore, our objective is to provide a method for mapping out conceptual pathways based on clear definitions for theoretical components.

To accomplish this objective, we first define the theoretical components of a graphical model, and describe how to use this model for integration. As a specific example, we utilize a study on the importance of top-down versus bottom-up effects in food webs (Hoekman 2010) to demonstrate how one proceeds through our modeling process. Even though we present this process in a step-wise fashion, scientists arrive at hypotheses through a variety of paths (Bump 2007). We suggest the goal should be to identify the theoretical drivers of our research questions prior to conducting research (Prather et al. 2009, Crowl 2009). We describe the benefits and pitfalls of using this approach, and suggest that using this type of approach may facilitate integration among different sub-disciplines of ecology and biology, where integration is the linkage of different theory components across different domains.

Constructing a model of theory

Theory components. A theory, most broadly, is a system of conceptual constructs that organizes and explains the observable phenomena in a stated domain of interest (Pickett et al. 2007). Traditional definitions of the components of theory do not lend themselves readily for use in ecology. Consequently, ecologists have modified these terms for better application to ecological theory. For clarification, we present a description of classic philosophy of science definitions for terms used in this text (Flew 1984, Lacey 1996), along with the basis for our usage (Pickett et al. 2007) and modified definitions (Ford 2000) used by ecologists (Table 1).

Hypotheses originate from the identification and assembly of conceptual constructs and empirical facts pertinent to the proposed research question. Conceptual constructs are abstractions of reality and include: (1) assumptions – speculations about the construction of the study system, the interaction of its components and the manifestation of possible dynamics, (2) concepts – specified ideas dependent on the identification of the assumptions (Table 1), and (3) definitions – establishment of important parameters such as limits and units. Both concepts and definitions arise from the assumptions of a theory. Similarly, the objects, interactions and states that are the subject of theory must be clearly defined. As an example (from Pickett et al. 2007), competition is a complex concept that may be defined as the process of concurrent use of a limiting resource by more than one organism. This process-based definition determines how an ecologist would measure the effect of competition: a difference in amount or availability of a resource used by both organisms when together or separate. Alternatively, defining competition as the negative effect of an interaction suggests measuring densities of the organisms when together or separate. Therefore, careful specification of the conceptual constructs is essential - many debates about the importance of ecological factors have occurred when researchers did not clearly define what was tested (e.g., McIntosh 1985, Belovsky et al. 2004).

Empirical facts are confirmable observations (compare with “axiom” from Ford 2000, Table 1), while the condensation of a large body of facts comprises confirmed generalizations. Because facts are given meaning by the theory to which they contribute, it is useful to distinguish between accepted facts that precede a theory, and the new observations under investigation (Pickett et al. 2007).

Laws and models (Table 1) are then derived from conceptual constructs and empirical facts, but are more sophisticated than these elements because they contain an internal logical structure and are capable of generating predictions. Laws are quantitative or verbal statements that specify an empirically supported correlation or causal relationship between two or more constructs or facts. The important feature of a law is generality throughout a specified domain (Table 1; for extensive discussion, see Kuhn 1962, Picket et al. 2007, Dodds 2009, and references therein). Models are constructs that explicitly distill assumptions, concepts, confirmed generalizations, and laws into a simplified representation of reality (Table 1). Several types of scientific models are recognized by ecologists including verbal, quantitative, graphical, or physical (Levins 1966, Haefner 1996, Williams et al. 2001). Even though many models can be idealized in a quantitative form, each represents a trade-off between generality, precision, and realism (Levins 1966).

Although laws and models may generate hypotheses, the abstractions they represent must be translated for application in the specific field or laboratory setting (e.g., species and study site) in which the hypotheses are to be tested. Translation requires the researcher to address issues such as how abstract concepts will be measured or how change will be detected. In this way, translation bridges the theoretical aspects of a research question with the realities of empirical testing. Proper translation of laws and models results in predictive statements—hypotheses—that are tested within the spatio-temporal domain specified by the researcher (*see below*). Biological, statistical, and theoretical results from the experimental tests of the hypotheses can then refine the set of concepts, facts, laws and models used to initially formulate the hypotheses, denoted by bold back arrows in Figure 1, as well as refine theory components of other domains—what we define as integration and inference (i.e., dashed output arrows).

Before discussing how integration occurs, we must first define the domain terms represented in Figure 1. We propose that the domain (*sensu* Pickett et al. 2007, Table 1) encompasses the space, time, phenomena, and level(s) of biological organization addressed by a theory. For example, Scheiner and Willig (2011) define the broadest domain of ecology as the ‘spatial and temporal patterns of the distribution and abundance of organisms, including causes and consequences.’ While the concept of domain is related to modeling scale, the domain includes numerous sub-domains from which concepts, facts, laws or models are either distilled from other domains or the present domain. The ways these sub-domains are linked reveal a key benefit of our proposed graphical model: researchers can explore relationships among (sub-) domains, enabling theory integration and identification of gaps in our understanding (i.e., poorly understood linkages). Several constituent theories have been proposed such as population dynamic theory and a metabolic theory of ecology (Pickett et al. 2007, Scheiner and Willig 2011, Dodds 2009), and these may provide an initial standardized basis for ecological domains. Results of a given study may then lead to expansion or refinement of a theory domain, and could even suggest the need for development of new theoretical domains.

In Figure 1, the spatio-temporal extent in which the hypothesis formulated by the researcher is tested forms the sub-domain A. For simplicity, we suggest that the researcher limits the scope of the sub-domain A by the extent of the hypothesis. A criterion for inclusion of an element within a domain is whether the understanding of the item can be directly refuted or changed by a hypothesis test within the domain. Therefore, concepts, facts, laws or models that aid in the formulation of the hypotheses but reside outside the scope of the domain in which the hypothesis is tested (e.g., sub-domain A) are assigned to other sub-domains (e.g., B and C). Similarly, it is this sub-domain A where the spatio-temporal extent of a study is defined, for example, as the areal extent of a specific study site (e.g., a wildlife refuge) during a given time period (e.g., summer months over 3 years) when one or more interacting focal species are present (e.g., specific ungulate prey and their predators). In this example, models from predation theory (e.g., Lotka-Volterra predation) would reside in a different sub-domain (B or C), as would results from prior testing of food web theory.

Integration. Integration occurs when theory components are linked across different domains through their distillation as sub-domains. While formulating a hypothesis, four avenues of integration (Integration Routes – IR, dashed lines in Figure 1) among domains are possible:

- IR 1: Results from the test of a hypothesis in sub-domain B refine the concepts and facts of sub-domain A. Example: Results from studies examining the non-consumptive effects of predators on the habitat choice of prey populations combined with results from studies that demonstrate differences in susceptibility to disease of the prey based on habitat choice can be combined to form a new hypothesis on the effects of predation risk on disease transmission of the host-prey population.
- IR 2: Results from the test of a hypothesis in sub-domain B refine the laws and models of sub-domain A. Example: A researcher has developed a model of primary productivity for streams. Recent research from terrestrial systems suggests that the different decomposition rates of leaves have a strong impact on nutrient cycling. The researcher then derives a new model that incorporates variables for fast and slow decomposing species of allochthonous inputs.

- IR 3: The researcher derives a new law or model for sub-domain A from concepts and facts established in sub-domain C. Example: A researcher interested in predicting optimal foraging strategies under the risk of predation may draw from economic concepts (e.g., cost-benefit, diminishing returns) to model the foraging decision process as a trade-off between foraging and predator avoidance. The distinction between IR 2 and IR 3 is how different components (i.e., results from hypothesis testing vs. established concepts and facts) from other sub-domains influence the laws and models of sub-domain A.
- IR 4: The researcher translates a law or model from sub-domain C into a testable hypothesis in sub-domain A. Example: Within sub-domain A, a researcher has developed a species-specific model for trading off feeding time in particular environments with minimizing heat stress in those environments. In order to translate that model into testable hypotheses, the researcher utilizes thermodynamics models of heat exchange between organisms and their environments to make specific testable predictions related to heat stress while foraging.

We do not include integration routes between identical components (e.g., laws and models of sub-domain C to laws and models in sub-domain A), under the assumption that these are already part of the current theory domain (sub-domain A). Furthermore, the conceptual constructs must be precisely defined as described above; otherwise the integration routes may collapse into IR 1. After a study is completed, results can not only refine components within the specified sub-domain (bold arrows in Figure 1), but also link theory components with other domains through various output integration routes (dashed arrows in Figure 1).

An example application of the model: the relative importance of top-down vs. bottom-up

effects in food webs

Here we illustrate the use of this graphical model with an example from our own research which focused on factors that modulate the relative importance of top-down (i.e., predator effects on prey) and bottom-up (i.e., resource availability effects on consumers) control in food webs (Hoekman 2010). Specifically, this study began by asking how temperature affects the relative importance of predators and resources in regulating population density of species. We then focused on the species residing in pitcher plants, *Sarracenia purpurea*. The domain for this research (Hoekman 2010) included numerous sub-domains (food web theory, population regulation theory, metabolic theory) from which conceptual constructs, facts, laws or models were distilled (Fig. 2). These components aided in the formulation of the hypotheses but reside outside the scope of the sub-domain in which the hypotheses were tested – the pitcher plant sub-domain. This nomenclature does not imply that the sub-domain is only spatially defined, but refers to all of the theoretical structural and functional components of pitcher plant communities.

The *concepts* of top-down and bottom-up control have been well developed by prior researchers (Carpenter et al. 1985, Hunter and Price 1992), including predation, competition, decomposition, and nutrient cycling (DeAngelis 1992). These concepts include assumptions about the interactions between species (e.g., the species are proximate) and were defined for the pitcher plant sub-domain. For example, top-down and bottom-up effects were measured via changes in species density (protozoa) or biovolume (bacteria). The *empirical facts* pertinent to this research describe the model system employed, the pitcher plant inquiline community. This community consists of mosquito larvae that consume protists and bacteria which consume detritus (reviewed in Miller and Kneitel 2005). The spatio-temporal extent was defined by these small aquatic communities within pitcher plants, which grow in bogs and other wetlands throughout Eastern North America. Although the seminal work on top-down and bottom-up effects demonstrated that they can occur in lakes (Carpenter et al. 1985), the *sub-domain* A of inference of this particular study is limited to small aquatic habitats (pitcher plants, Fig. 2). This study may also expand the domain of population regulation theory by top-down and bottom-up control.

Laws and *models* were derived from the conceptual and empirical components described above and from integration with other sub-domains (food web theory, Fig. 2). Food web models provided a framework for the interactions of community members. Using the concepts and empirical facts above we *derived* a food web model for a pitcher plant inquiline community incorporating both nutrient inputs through decomposition (DeAngelis 1992) and predation (Hairston et al. 1960, Schmitz 1992). Furthermore, drawing from observed relationships between temperature and metabolism (i.e., empirical facts) which form the basis of metabolic scaling laws (metabolic theory, Fig. 2), we made predictions about the effects of temperature on the members of this community.

These laws and models were *translated* into specific *hypotheses*. Applying the metabolic scaling laws to the derived inquiline food web, we hypothesized that an increase in temperature would accelerate top-down processes via predator metabolism resulting in increased feeding rates. An increase in temperature was also hypothesized to accelerate bottom-up processes by promoting greater bacterial productivity resulting in faster decomposition rates. Furthermore, the relative strength of top-down versus bottom-up effects would depend on temperature. Translating these hypotheses further, top-down influences were defined as the number of predators (mosquito larvae) whereas bottom-up influences were manipulated by the density of resources (ant carcasses). These hypotheses were *tested* with factorial experiments manipulating top-down and bottom-up effects across a range of temperatures (Hoekman 2010).

Illustrating Integration Routes. When first developing this study, the questions were approached from the perspective of a graduate student of community ecology – working from within the domain of food web theory. While the importance of climate on ecological interactions was appreciated, formally mapping out linkages between food web and metabolic theory provided a key insight into understanding this system. A central component of metabolic theory consists of scaling laws derived from empirical facts collected from a wide range of spatial and temporal sub-domains (e.g., Brown et al. 2004). By translating these scaling laws to the pitcher plant inquiline community we linked metabolic theory to our theory through IR 4 (Fig. 1). For example, our hypotheses about how invertebrates in pitcher plants would respond to experimental warming were based on a general relationship, or law, that is itself based on multiple published accounts of metabolic responses to temperature. Results from testing hypotheses about top-down and bottom-up effects in different communities provide the conceptual constructs for our model through IR 1. Food web models developed from results of hypothesis testing in different systems were modified for application to pitcher plant communities via IR 2. Results from this study may be applied to other aquatic or detritus-based systems via output integration routes (e.g., IR 1, 2 for another sub-domain). For example, the strength of top-down effects was found to increase with temperature in this sub-domain. This result provides an empirical fact (i.e., the measured response in this study), as well as a conceptual construct (i.e., increased temperature increases top-down control) in a specific community (i.e., pitcher plant inquilines). Drawing from predation theory, one could derive a temperature-dependent functional response model and relate this to inquiline food webs to develop new hypotheses. Consequently, a key insight gained through this process was to link components of metabolic theory through predation concepts to food-web models to generate novel hypotheses, thereby broadening conceptual horizons for the researcher.

Applications of the model by researchers

Outlining a new research project is a daunting task regardless of prior experience. The model presented here is intended to help structure the design process by sharpening the focus of research based on existing theory. This approach will enable scientists to form meaningful and novel questions, and facilitate the integration of their work with other research. We suggest that scientists from all levels of experience should use this framework to graphically organize and present their research in an explicit theoretical context, and we promote including these graphical models as publication supplements to facilitate integration. The way researchers approach the model will vary depending on where they are in their career, and below we discuss how this model may be applied at different points in a research career.

Beginning graduate students. After a general question is identified (for suggestions on generating novel questions see May 1999, Belovsky et al. 2004, Bump 2007) the student needs to return to the literature and address several questions to develop a model. 1) Has this question been answered before in another domain? 2) What are the conceptual constructs I am employing in asking this question? 3) What are the confirmed generalizations I am employing and how do they influence my sub-domain? 4) What existing laws and models are incorporated in my question and how are they derived from my conceptual constructs and empirical facts? At this point the student should use the answers to amend the rest of the model, fill in the 'laws' and 'models' boxes and then use translation modes to formulate a testable hypothesis.

Experienced graduate students. Students who have already tested their hypotheses or are midway through their research can develop the model retrospectively. After developing their model, students should proceed with a thoughtful analysis to answer the following questions. 1) Are there logically weak points in the project? 2) Does the research address any missing components in the theory? 3) How can the results be generalized to return to the original theory? 4) What components of the theory are changed by these generalizations? These questions should enable the student to visually identify how their research project fits into current theory. This process may identify additional questions to complement the existing project or help to identify weak areas. Rather than be discouraged, identification of conceptually weak points in the research can be viewed as an opportunity to directly address potential gaps before reviewers point them out. Students may use the model as a guide to integrate the different dissertation research chapters with each other as well as relate their work back to the larger body of literature.

Established researchers. Implicitly, scientists with greater experience have the advantage of intimately knowing the conceptual constructs related to their favorite study organism/system/process. From experience, they may typically employ well-established laws and models derived from these conceptual constructs. Still, it can be advantageous for established researchers to adopt this graphical model for the visualization of where their current work fits into existing theories, and envision linkages with other sub-domains. By identifying the broader impacts of their research, investigators can strengthen the theoretical foundations for new research, for example, in grant proposals.

Benefits and pitfalls of using this approach

To evaluate both benefits and pitfalls of using this graphical approach, we employ a point-counterpoint analysis. Many benefits described overlap with Belovsky et al.'s (2004) suggestions to advance ecological science (marked with an "*").

- **Benefit:** Mapping out explicit linkages of theoretical components will help to correct a perceived lack of appreciation of classic literature* and provide better links between empirical, theoretical*, and natural history*. In completing this graphical model, researchers will trace the theoretical roots of their hypotheses to the older papers that newer researchers often ignore when using digital databases, including the more purely theoretical papers that can easily be ignored by those interested in empirical research and vice versa.
- **Pitfall:** Devoting time to catching up on the classics could detract time from reading current literature. However, this better understanding of classic research and how it relates to what younger researchers perceive as novel ideas could also allow for avoidance of bandwagons*, i.e. research topics that go in and out of vogue without much resolution. It would also prevent the unintended repetition of previously conducted studies (Belovsky et al.2004).

- **Benefit:** The process of defining concepts while mapping out a theoretical framework can help identify multiple meanings or ambiguities of concepts in the literature. A thorough review could lead to a publication that clarifies the issue(s) or helps to resolve disputes in the literature.
- **Pitfall:** Devoting time to clarifying a conceptual issue could detract time from primary research, and be considered a less useful endeavor for students or junior researchers.

- **Benefit:** Understanding how multiple studies across different spatial and temporal scales expand the domain of a theory could increase replication over time and space in ecological studies*. This can lead to greater rigor if researchers follow similar methods as the studies they are attempting to replicate.
- **Pitfall:** In replicating published studies, researchers run the risk of having their studies rejected by high impact journals – a consideration that is often so important in acquiring jobs and in the tenure process. This phenomenon could also lead effectively to scientists being caught in what Kuhn (1962) called periods of "normal science" as opposed to research that leads to scientific revolutions, i.e. ever more specific refinement of existing theory rather than pushing the limits to explore new terrain beyond established theoretical grounds. In attempting to make ecology a more rigorous scientific discipline with better resolved concepts, surely greater replication of experiments which expand the domains of existing ecological theories is necessary.

- **Benefit:** This graphical process may open new avenues for integration across disciplines, and show instances where new theoretical domains could be developed. Seasoned researchers may reassess the sub-domains of their work, and identify linkages between their individual projects and potentially new avenues for investigation. Indeed, some of the most new and exciting theoretical developments in ecology have come from using theoretical constructs from very different domains (e.g. the use of economic models for foraging theory).

- **Pitfall:** Using different methods from very different disciplines can be time consuming and frustrating especially in the early stages, and use many research resources.

Theory integration and scientific progress

The graphical model we present here provides a way for researchers to articulate the theoretical components of their research. For example, carefully describing conceptual constructs including concepts, definitions and assumptions will facilitate communication among researchers (Grimm and Wissel 1997, Belovsky et al. 2004, but see also Hodges 2008). By the time the results are analyzed, an explicitly defined sub-domain provides the inference space for generalization, and the framework may directly point towards the next question(s) worthy of investigation. Making components explicit eases tests for logical consistency and agreement with results. Testing weak links (e.g. testing an assumption based on weak support from data) efficiently enables rapid progress of maturing theories by evaluating the pillars on which they are built. While this approach may enhance progress within a sub-discipline, the graphical model also highlights the links with components of other theory domains (e.g., ecological sub-disciplines) through the integration routes of its components. Understanding these integration routes may enhance the dialogue between empiricists and theorists, by elucidating the interaction between data and models (e.g., Kareiva 1989, Belovsky et al. 2004). Integration follows by investigating the linkages either among or within sub-disciplines. For example, studies employing the same theory but applying it in a different geographical region or system (e.g., moving from lakes to forests), may reinforce (if the data do not support) or expand (if consistent) the current domain of the theory. An explicit framework will also enable direct comparisons across studies in order to refine component models or laws. Rather than contributing to a debate about whether ecology has general laws as in other sciences (Lawton 1999, Turchin 2001, Colyvan and Ginzburg 2003, O'Hara 2005), reproducing studies in light of this graphical model provides a means for evaluating the invariance (Lange 2005) of the laws (as model components) across new spatio-temporal domains (i.e., against "counterfactual perturbations," Lange 2005). To the extent that the laws would be invariant under repeated tests of their translated predictions, they would gain support, aiding in maturation of existing theories while enhancing scientific progress – especially in ecology.

Acknowledgements

This manuscript is the product of a graduate seminar on Philosophy of Ecology at the University of Notre Dame, and other seminar participants contributed to discussions of these ideas. We thank S. Scheiner, T. Miller, and several anonymous reviewers for insightful comments on earlier drafts.

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527 **Table 1.** Comparison of definitions of common philosophy terms. Words in italics are

528 synonyms used by the source for the given term.

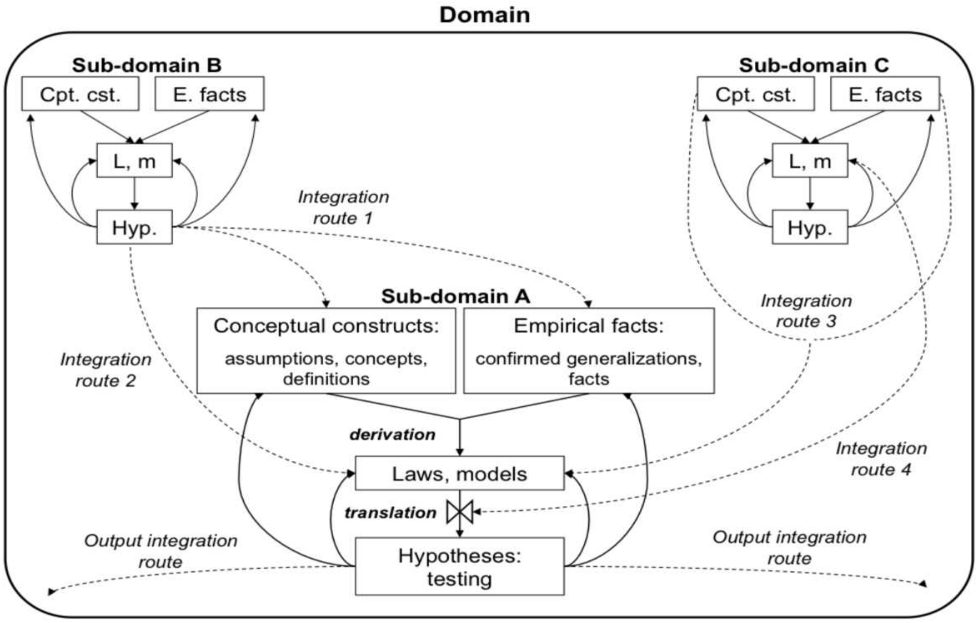
Term	**Classical philosophy**	**Ford (2000)**	**Pickett *et al.* (2007)**
Concept	Sentences, statements, propositions, beliefs, theories, and doctrines that can be said to be true or false[a]	Any object or idea to which we can give a name and define, and so enable things to be understood in a particular way	Labeled regularities in phenomena
Confirmed generalization	*Universal generalization* - An inference from a premise true of any arbitrarily chosen individual, to a conclusion about every individual[a]	*Over-arching axiom* - A fundamental proposition, used as an axiom, which states broad assumptions of the theory and cannot be challenged directly by single investigations	The condensation of a large body of facts
Domain	Set of the individuals which enter into the argument of a function[a]	The limitations to the importance and application of concepts	The scope in space, time, and phenomena addressed by a theory[b]
Empirical fact	Usually, that which corresponds to a statement or makes it true[c]	*Axiom* - A proposition assumed to be true on the basis of previous research, observations, or information, and is used in defining the working part of the theory that is the foundation for the research	Confirmable record of phenomena
Hypothesis	A prediction based on theory; an educated guess derived from various assumptions, which can be tested using a range of methods, but is most often associated with experimental procedure[d]	A statement that will be tested by investigation	Testable statements derived from or representing various components of theory
Integration	*Synthesis* - combination of separate parts into a unified whole[a]	*Scientific inference* - conducted for a specified question using the following procedures and standards:	The explicit joining of two or more areas of understanding into a single conceptual-

		1. A synthesis must be made of new results with existing theory 2. The synthesis provides a scientific explanation of why something exists or occurs 3. Scientific explanation must be coherent, explaining new and previously obtained information	empirical structure[b]
Law	A rule or generalization which describes specified natural phenomena within the limits of experimental observation[d]	An empirical relationship between two or more concepts, established by measurement, and asserted to be universally true	Conditional statement of relationship or causation, statements of identity, or statements of process that hold within a universe of discourse
Model	An interpretation of the set of axioms of that system[e]	Describes important features in a simplified representation of a system and can be used to illustrate how interactions may take place to produce particular outcomes	Conceptual construct that represents or simplifies the structure and interactions in the material world
Translation mode	N/A	*Data statement* - 1) defines the scientific procedure to be used in investigating a postulate, 2) specifies the measurements to be made for each concept of a postulate and 3) specifies the requirements of the data for any statistical test to be applied	Procedures and concepts needed to move from the abstractions of a theory to the specifics of application or test or vice versa

Notes: [a] – Mautner (1997); [b] – Definition differs from the one used in paper, see text; [c] – Lacey (1996); [d] – Walker (1998); [e] – Flew (1984).

Figure 1. Graphical model of theory integration. Abbreviations represent: Cpt. Cst =conceptual constructs, E. facts = empirical facts, L, m = laws, models, Hyp. = hypotheses: testing. The focal study is represented in Sub-domain A with all theory components interacting as explained in the text (theory component interactions = solid lines), and draws components from both Sub-domains B and C through four different Integration routes (integration routes = dashed lines). Results from the study conducted in Sub-domain A can inform studies within the same sub-domain for refinement or studies within other sub-domains (output integration routes).

Figure 2. An example of the graphical model filled out to summarize a paper based on a chapter in a dissertation (Hoekman 2010). While this figure only encompasses a single sub-domain, its components are derived from multiple domains.



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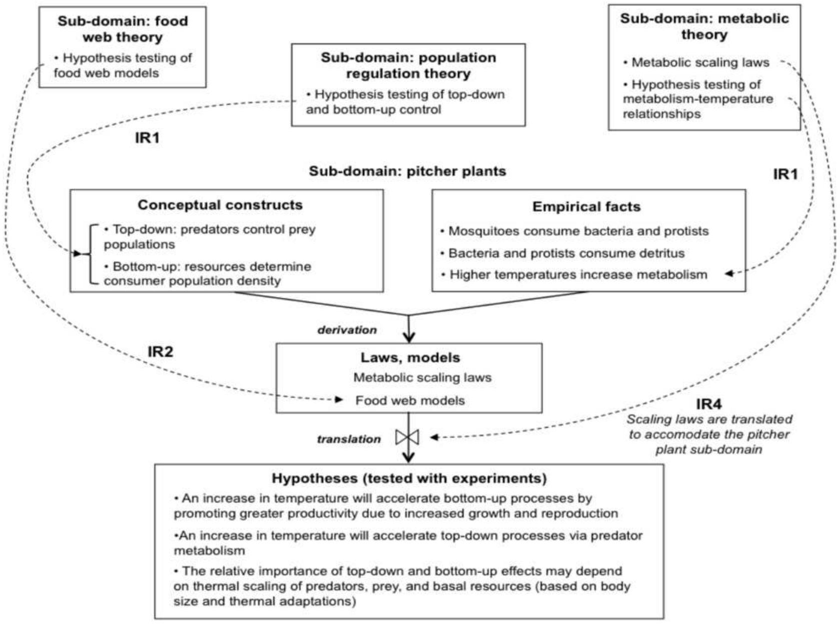

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